ADAPTIVE CONTROL FOR PARTIALLY KNOWN SYSTEMS

Theory and Applications

CARLOS A. CANUDAS DE WIT

STUDIES IN AUTOMATION AND CONTROL

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STUDIES IN AUTOMATION AND CONTROL

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*All knowledge is of itself of some value. There is nothing so minute or inconsiderable, that I would not rather known it than not**.

To my parents :

Alfonso and Amanda

* Dr Johnson in Boswell's *Life of Johnson, 1975.*

Preface

Scope and Approach

Adaptive control has been considered as an alternative to design high-performance control systems from the beginning of the 1950s. Since then, most of the adaptive control schemes have been formulated either in the continuous-time or in the discrete-time framework. Both approaches commonly use "black-box" models for describing the process to be controlled; models with known structure but unknown parameters. These models have the advantage that they are general but also the disadvantage that many parameters have to be estimated. There are in practice, however, many adaptive problems where the system can be described as partially known in the sense that part of the system dynamics is known and another part unknown. This is the kind of system considered in this book.

Most of the adaptive algorithms that are reliable--in the sense that they guarantee closed-loop stablility and some performance behavior-- require to some extent some system knowledge (sign and bounds on the process parameters, rate of the parameter variation, etc.) and a checking procedure for the caution update of the parameter estimates. In this vein, continuous-time algorithms are naturally adapted for using the available process information but ill-equiped for adding any checking procedure which supervises the estimates' quality. Conversely, discrete-time adaptive controllers are well adapted for implementing "safety nets", but the incorporation of the physical process knowledge is not trivial (the mapping between the continuous-time and the discrete-time parameters is often non-linear and non-bijective).

In the middle of these two previous approaches lies an alternative choice: *Hybrid adaptive controllers*. The control design is then realized entirely in the continuous-time domain while the estimation loop is performed via recursive algorithms. This approach retains the advantages of the previous two schemes. This is the class of adaptive controllers that this monograph is concerned with. It will comprise two parts:

The first part (Theoretical, from Chap.2 to Chap.6) will present the adaptive algorithms and study their stability and convergence properties. Particular emphasis will be placed on the interpretation of the results. It will be assumed that the reader is familiar with some basic notions of linear control theory, digital systems, estimation, filter theory and Lyapunov stability.

The second part (Applications, Chap.7, Chap.8 and Chap.9) will present some applications of the ideas discussed in previous chapters. These study cases deal with applications in the robotics and aero-space fields. In the Author's wishes, they may be of special interest to practising engineers confronted with designing adaptive control systems and they will give an appropiate guidance for potential users of the adaptive techniques.

Outline

Chapter 1 is an introduction to adaptive control in partially known systems. It intends to serve as a motivation for the following chapters as well as to place the monograph in the proper context of adaptive control systems. A concise, but brief, summary of the recent work carried out in this particular class of adaptive control schemes is also presented. It also describes the class of plants this monograph is concerned with: physical systems which can be split in one known part and another which is unknown or time-variant. Different model structures for these systems are also discussed as well as the expected improvements of this approach: reduction of the estimated parameter numbers, numerical robustness, increase of the convergence rates and relaxation of the convergence conditions in terms of frequency contents of the input-output process signals.

To estimate the continuous-time process parameters via recursive algorithms, several approaches are studied in *Chapter 2*. A method which uses sampled states of the input-output process signals to avoid the measurement of the time-derivatives is extensively analysed. Some of the algorithm's properties are explored in terms of the system's signals richness. Guidelines for choosing the design variables are also given. Alternative methods based on discrete-time models which approximate the time-derivatives by interpolating two consecutive measures are also discussed. This chapter is primarily based on Canudas de Wit[86].

Chapter 3 deals with physical systems similar to those treated in Chapter 2, but subject to bounded disturbances. The main assumption is the knowledge of the disturbance upper bound. Based on this, a new algorithm is proposed. The notions of "dead-zone" and "lack of information" are analysed. The chapter ends with a discussion of the nature of these disturbances (external noise or neglected process dynamics) and gives some examples illustrating the effects of an over/under estimation in the disturbance bounds. The body of this chapter is mainly based on Canudas de Wit & Carrillo[86].

Systems with unknown delay are treated in *Chapter 4*. A simple technique is presented for on-line estimation differential-delay systems (extensions of the ones considered in Chap.2, which are assumed to have an unknown or no delay). A major advantage of the algorithm lies in its ability to track time-delay variations over a practically unlimited range. The technique is based on the appproximation of time delay in the frequency domain by a rational transfer function (using Padé approximation) and estimation using a non-linear model in the desired parameters (Agarwal & Canudas de Wit[86]).

Chapter 5 discusses the control policies to be combined with previously described estimation algorithms. They belong to the family of the adaptive control systems called: *"Indirect adaptive schemes"* . For these, first a linear controller is designed based on a process model with known structure but unknown parameters; in a second step an estimation loop is added to estimate the model parameters and to track its possible time-variations. In particular, we deal with hybrid controllers which fit in a very natural manner with the type of estimation algorithms described throughout the previous chapters. Conclusions of the first part of the monograph will be given in *Chapter 6*.

Chapter 7 describes an application of the aforementioned adaptive techniques to compensate the friction effects often found in DC motor drives. Friction is responsible to some extent for a poor performance in precision servos in robots and other applications. The proposed scheme is a combination of a fixed linear controller and an adaptive part which compensates for nonlinear friction effects. Experiments and simulations show the improvements attained (Canudas de Wit, Astrom, & Braun[86]).

Chapter 8 gives another application of adaptive control systems in a very flexible robot arm. This type of systems is of interest in the aero-space industry. Due to their oscillatory and non-minimal phase nature, they are difficult to control. Their modes change considerably when pay-load mass variations occur and then the performance provided by a pre-tuned linear controller may be no longer satisfactory. Although adaptive controllers then provide an interesting alternative, it is necessary, however, in their classical approach, to tune many parameters in order to satisfactorily characterize modes of the arm. This leads to very long convergence periods or demands too much chattering in the control law activity. Through an extra modeling stage, an adaptive control scheme is proposed (Canudas de Wit & Van Den Bossche[86]). It only requires the estimation of one parameter (pay-load mass) which is an improvement with respect to the classical approaches.

The precision and tracking capabilities of the industrial robots are often limited by the presence of some degree of flexibility in the mechanical links transmiting the drive torque to the drive points. *Chapter 9* presents a robust control scheme based on an independent joint robot model using only measurable actuator signals. An estimation mechanism for identifying the robot's model parameters including joint flexibilities is also presented. The first step consists in estimating the parameters associated with the rigid robot model, by a off-line procedure. The complementary model parameter set are subsequently estimated in conjuction with an hybrid adaptive observer. A study case of a robot manipulator with compliance at the joints shows the potentialities offered by this approach.

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C. Canudas de Wit Grenoble, November 1987.

Contents

1. Introduction

The research in the field of adaptive control has been focused from different points of view. Some of them concern the study of the analytical phenomenas of the non-linear and time-varying nature of the adaptive algorithms, whereas others attempt to apply these algorithms in a reliable manner and are mainly concerned with implementation problems. The meaning of the *a priori process knowledge* and its use may vary considerably from one point of view to another. For the former, the question may probably be stated in terms of *minimun* a priori plant knowledge necessary for stabilizing the plant, see for example, Martensson[86], and references therein. Within this context, the answers provided often lead to "existential-type" results. This of course limits its applicability. On the other hand, practicians may be conversely interested to include the *maximum* available plant knowledge in order to render trustworthy the adaptive loop. The inclusion of the process information by the latter, has been mainly done in a heuristic manner rather than in a proper mathematical formulation. The reason probably is the lack of a general model structure suitable for introducing all possible plant information sources.

In this book, the meaning of the *a priori process knowledge* will be related with all the physical plant information that can be included in order to reduce the number of the model parameters to be estimated. We shall not explicitly formulate the problem in terms of a known class of plants to which the system belongs. Neither in terms of the controller's class which stabilizes the system. We shall